Monitoring the Percussive Welding Process for Attaching Wires to Terminals

By J. C. COYNE

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At present, no satisfactory nondestructive test is known which can be practically applied in the shop to detect a weak percussive-welded connection. Also, the breaking strengths within a population of percussive welds are distributed in such a way that large sample sizes are needed to determine, with reasonable confidence, if the population contains an excessive number of weak welds.

Monitoring the duration of the welding arc and the approach speed of the wire, for each weld as it is made, has been found to provide an effective control of the process. An analysis of the process yields necessary conditions which the arc duration and wire speed must satisfy. Test data are presented which confirm the necessity of these conditions, and show that when they are satisfied, percussive-welded connections can meet quality objectives.

I. INTRODUCTION

The low-voltage percussive welding process as applied to wired connections has been described and its merits pointed out in previous papers.[1–6] Therefore, only a brief review is included here.

Percussive welding is a form of capacitor discharge arc welding. The parts being welded, in this case a wire and a terminal, are themselves the only necessary electrodes (see Fig. 1). Also, the only advance preparation of the electrodes needed is to cut a tip on the wire end. The weld is made by propelling the wire across a 50-volt gap toward the terminal. When the two are nearly touching, an arc is established between the wire tip and the terminal. Initially, the power surge in the arc develops sufficient heat to melt back the wire tip faster than the electrodes are closing. But, with time, the power decays and melting slows down until eventually the electrodes impact, extinguishing the arc and completing the weld. A welding voltage of 50 volts is commonly referred to as "low voltage" as opposed to "high-voltage percussive welding" used to attach the fixed contacts to the wires of the wire spring relay.

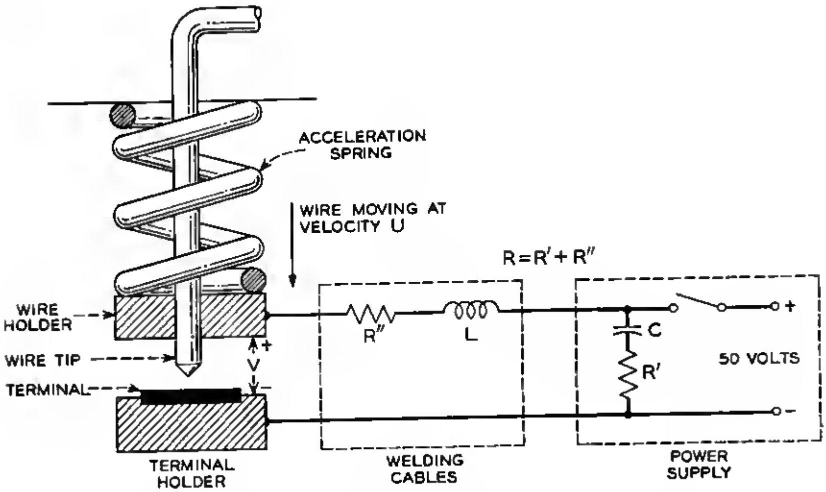

Fig. 1 — Welding circuit.

The welded joint made by this process is usually as strong as the wire itself. Nevertheless, it appears to be characteristic of the process to produce also, if adequate controls are not present, a small scattering of weaker welds, some ranging nearly to zero strength. Naturally, such a distribution of weld strengths is unacceptable from a connection reliability standpoint. Moreover, the usual statistical sampling techniques for assuring satisfactory quality in production have limited value here, as shall be seen later. For this reason, other more effective measures were sought.

Extensive investigations were first conducted to find a nondestructive screening test which might be applied to each completed weld. However, at the present time no satisfactory test has been devised which can be practically applied in the shop. More recently, attention has centered on control of the process by monitoring certain important welding parameters as each weld is made. The analysis and tests pertaining to monitoring are the subjects of this paper.

In the preliminary investigations, the time histories of wire velocity, current, and voltage were examined for aberrations which always coincided with the occurrence of a bad weld. Although this study revealed no easily measurable, consistent predictor of bad welds, it was observed that welds were consistently good if the time duration of the arc was within a certain range. Conversely, the percentage of defective welds increased for either longer or shorter times. Also, this optimum range

shifted, compressed, or expanded depending on the welding circuit constants, the wire velocity, and the wire tip shape.

Further testing and analysis were done to explore the effectiveness as well as the practical possibilities of monitoring arc duration. Two factors seemed to be in favor of this. First, the arc duration is a sensitive indicator of most possible changes in welding conditions. For instance, variations in the electrical characteristics of the welding circuit, wire tip geometry, or approach speed of the wire will all affect the duration of the arc. Second, it is a relatively simple measurement to make.

The areas of fractures for welds occurring at either very short or very long arc durations were observed to have certain distinguishing characteristics. In the case of very short arc durations, the welded area is usually noncircular and has less area than the cross-sectional area of the wire, as shown in Fig. 2(a). This results from the fact that the chisel-shaped tip on the wire does not become completely melted back during the short time duration of the arc. For the same reason, the crater burned into the terminal is usually undersized. The loss of weld strength in this case depends on the reduction of weld area.

In the case of very long arc durations, the smooth break along the interface of the two metals indicates an absence of fusion and suggests that the molten metal film over the electrodes had prematurely solidified. Fig. 2(c) shows an extreme example of this. This type of weld is invariably quite weak. As the arc duration is shortened, a corresponding increase in the average area of fusion in the weld is observed, but with considerable variability. A comparable improvement in the average weld strength also occurs.

If the arc duration is further shortened until it is in the optimum

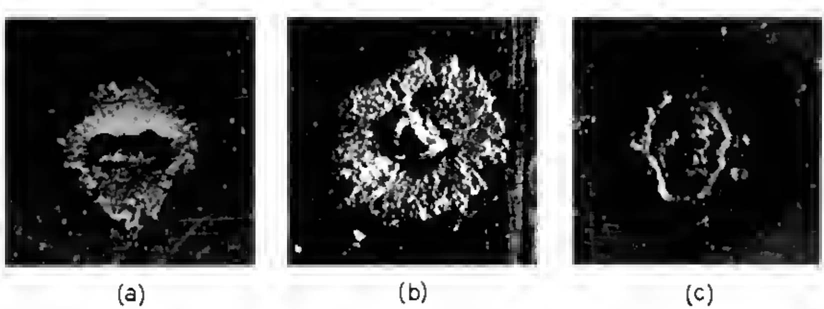

Fig. 2 — Appearance of weld breaks: (a) Excessively short arc durations do not provide sufficient melting energy and result in a weak weld due to the reduced area of fusion. (b) Arc durations within the optimum range result in a strong weld. (c) Excessively long arc durations allow excessive heat conduction losses and result in a weak weld due to premature solidification.

range (assuming that certain other conditions are also satisfied), then a full-area weld of wire to terminal will result as shown in Fig. 2(b), and the weld strength will equal or exceed the wire strength. The other conditions referred to above include: (*i*) No serious geometrical disparities in the surfaces of the arcing electrodes which would prevent a uniform full-area mating when contact is made. (*ii*) Adequate melting to remove the entire wire tip. (*iii*) No spreading or other disturbance of the arc due to surrounding fixture metal at electrode potential being too close. (*iv*) Development of sufficient force between electrodes at contact to effect good mating and fusion.

The foregoing observations suggest that premature solidification is a major cause of partial-area fusion. Excessive heat losses will occur at long arc durations, since the arc power decays at an approximately exponential rate, while the rate of heat conduction losses decreases inversely as the square root of time. Consequently, heat conduction losses grow with respect to arc power until eventually heat is being conducted away faster than it is being generated. Although radiation and convection losses are also present, these are small by comparison.

A second major cause for partial fusion in the weld zone is that the contours of the arcing surfaces can interfere with full area mating. This is particularly true at very short arc durations for reasons previously mentioned. However, to varying degrees, there will always be some differences in contour, because the two electrode shapes are vastly different at the start of the process. A proper choice of wire tip shape will minimize the disparity in the contours of the arcing surfaces. Any small differences that might still be present will not be harmful if the electrodes impact with sufficient force.

II. ANALYSIS OF WELDING PROCESS

2.1 *General*

Having seen in a descriptive way why either extreme of arc duration is undesirable, the welding process will be examined analytically in order to derive, for the general case, maximum and minimum monitoring limits of arc duration.

The major independent variables of the process to be used in this derivation are: (*i*) the wire and terminal metals; (*ii*) the welding voltage, V_o, which will be taken as 50 volts; (*iii*) the welding circuit effective resistance, R, and inductance, L, which will be treated as "lumped" constants; (*iv*) the power supply capacitance, C, also a lumped constant; (*v*) the wire velocity, U, which will be taken as the

average wire velocity during the time interval of the arc; (*vi*) the shape of the wire tip, especially its length, l, and volume, v.

The more important dependent variables to be used in the derivation are: (*i*) the welding current, I; (*ii*) the arc voltage, V; (*iii*) power expended in the arc, P; (*iv*) heat conduction losses, Q; (*v*) the burnback of the wire tip, b; and (*vi*) the arc duration, t_a.

2.2 *Some Relationships and Approximations Useful in the Derivation*

The first step in the derivation will be to establish useful relationships for arc voltage, current, power and heat losses. Wherever possible, approximations will be made to simplify the formulation.

The arc voltage (V) will be approximated by a straight line function, as shown in Figure 3:

$$V = V_1 - \frac{(V_1 - V_2)t}{t_a} \tag{1}$$

where V_1 and V_2 are the voltages across the arc just after arc initiation and just prior to arc extinction respectively. For copper wire and nickel-silver terminal metals, V_2 has been found to be approximately a 10-volt constant, independent of welding voltage and current, wire velocity, tip geometry, or wire gauge. Investigation of a few other metals also showed no appreciable variation from this 10-volt constant.

V_1 showed a slight dependence on the parameters previously mentioned, but in each case it was noted that an increase in V_1 corresponded to conditions producing a faster melting rate along the wire relative to

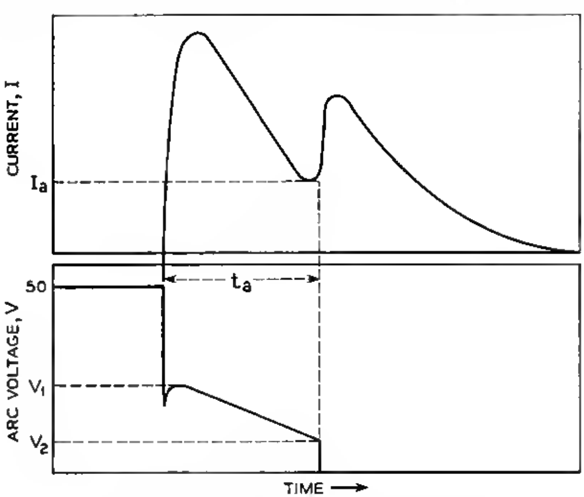

Fig. 3 — Typical traces of current and arc voltage.

the wire speed. For instance, V_1 would be increased if either the wire speed decreased or a longer and thinner tip were cut on the wire. In other words, it appears that the arc voltage is mainly a function of the instantaneous separation of the welding electrodes.

Although V_1 varied in the manner described, the magnitudes of the variations were small — in the order of 4 volts even when the peak welding current ranged from 300 to 900 amperes and the wire velocity ranged from 50 to 100 inches per second. A reasonable value for V_1, which will be used in the remainder of the analysis, was found to be 20 volts.

The differential equation describing the current flow for the welding circuit of Fig. 1 is:

$$L\frac{d^2I}{dt^2} + R\frac{dI}{dt} + \frac{I}{C} + \frac{dV}{dt} = 0 \tag{2}$$

with initial conditions at zero current and V_0 volts across C. Substituting (1) into (2), the welding current may be determined. The general solution for welding current consists of two parts: the standard "homogeneous solution" for a capacitor discharge through an RL series circuit, and an additive "particular solution" arising from the time dependent arc voltage function. The damping ratio of the welding circuit will be defined in the usual manner as the dimensionless ratio:

$$D = \frac{R}{2}\sqrt{\frac{C}{L}} \tag{3}$$

and confined to a range of one to infinity. For D equal to one (critical damping), the welding current becomes:

$$I = \left\{\frac{4(V_o - V_1)\tau}{R} - \frac{(V_1 - V_2)}{R}\,\frac{(2\tau + 1)}{\tau_a}\right\}\epsilon^{-2\tau} + \frac{V_1 - V_2}{R\tau_a} \tag{4}$$

where $\tau = t/RC$ and $\tau_a = t_a/RC$.

For D approaching infinity (zero inductance) the welding current becomes:

$$I = \left\{\frac{(V_o - V_1)}{R} - \frac{(V_1 - V_2)}{R\tau_a}\right\}\epsilon^{-\tau} + \frac{V_1 - V_2}{R\tau_a}. \tag{5}$$

For intermediate values of D, the current magnitude will be between (4) and (5).

When τ equals τ_a, either equation gives the current at arc extinction (I_a). If τ_a is sufficiently large, say greater than 4.0, then I_a from both (4) and (5) becomes

$$I_a \cong \frac{V_1 - V_2}{R\tau_a} \tag{6}$$

since in either case the exponential term becomes small by comparison.

If τ_a is not sufficiently large to use this approximation, then the contribution to I_a made by the exponential term should be included. Account is taken of this contribution by rewriting (6) with N substituted for $V_1 - V_2$:

$$I_a = \frac{N}{R\tau_a} = \frac{NC}{t_a} \tag{7}$$

where N is a number larger than $V_1 - V_2$ and dependent on τ_a. N may be calculated by equating (7) to (4) or (5), with $\tau = \tau_a$. Some representative values are shown in Table I, calculated for $V_o = 50$, $V_1 = 20$ and $V_2 = 10$ volts.

The instantaneous power, P, expended in the arc is the product of V, given by (1) and I, given by (4) or (5). At arc extinction, using (7) for I, and with $t = t_a$,

$$P_a = \frac{NCV_2}{t_a}. \tag{8}$$

The electrical energy, E_H, dissipated as heat in the arc, as a function of time, is obtained from a time integral of the power. To simplify the formulation without any great loss of accuracy, it will be assumed that the arc voltage remains constant (equal to V_1) and therefore the second terms of both (4) and (5) vanish. Then for $D = 1$

$$P \cong 4V_1 \frac{(V_o - V_1)\tau\epsilon^{-2\tau}}{R} \tag{9}$$

and for $D \to \infty$

$$P \cong V_1 \frac{(V_o - V_1)\epsilon^{-\tau}}{R}. \tag{10}$$

Using this approximation, the errors in arc voltage and current are of opposite sign, and therefore these partially cancel in the product. The remaining error is minimum at arc initiation and maximum at arc extinction. Table II has been prepared to show the relative magnitude of

TABLE I — VALUES OF N IN (7)

τ_a	$D = 1$	$D \to \infty$
2.0	17.87	16.77
2.5	14.64	15.33
3.0	12.50	13.97
3.5	11.27	12.85
4.0	10.62	12.03
4.5	10.02	11.39

TABLE II — ARC POWER VERSUS τ

τ	(5) times (1)	(10) (approximation)
0	$600/R$	$600/R$
1	$218/R$	$221/R$
2	$92/R$	$81/R$
$3 = \tau_a$	$47/R$	$30/R$

the error made by using tbe approximation. The calculations have heen made for $\tau_a = 3.0$ and for the same values of V_o, V_1, and V_2 used previously. Since the contribution to the total arc energy is many times greater at arc initiation than at arc extinction, it is evident that the percentage error is further reduced by the integration.

Therefore, for $D = 1$

$$E_H \cong CV_1(V_o - V_1)(1 - \epsilon^{-2\tau} - 2\tau\epsilon^{-2\tau}) \tag{11}$$

and for $D \rightarrow \infty$

$$E_H \cong CV_1 (V_o - V_1) (1 - \epsilon^{-\tau}). \tag{12}$$

The rate of heat conduction losses (dQ/dt) at any time after arc initiation can he taken as

$$\frac{dQ}{dt} = \frac{TkA}{\sqrt{\pi a t}} = \frac{K}{\sqrt{t}} \tag{13}$$

where A is heat conducting area; e.g., wire area,
k is thermal conductivity,
a is thermal diffusivity, and
T is molten metal temperature.

Substituting, for instance, the appropriate constants for 24-gauge copper wire, K hecomes approximately 7.0 watt $(\text{sec})^{\frac{1}{2}}$. This numher is based on using an estimated average value for T. There is evidence that some very small amount of copper vaporizes during arcing.[3, 6] Consequently, the molten copper must range between its melting temperature and its hoiling temperature.

The total heat conduction loss hetween arc initiation and time t is

$$Q = 2K\sqrt{t}. \tag{14}$$

2.3 *Maximum Limit on Arc Duration*

A maximum limit on arc duration, $t_{a(\max)}$, may now he specified in order to prevent premature solidification. It is required that the power

dissipated in the arc just prior to arc extinction always exceed heat conduction losses. Assuming half of the arc energy is expended at each electrode and that radiation and convection losses are negligible,

$$\frac{P_a}{2} > \frac{dQ}{dt} . \tag{15}$$

Implicitly, it is postulated here that if the above inequality is satisfied at arc extinction, then it must necessarily be satisfied for all earlier times.

Substituting (8) and (13) into (15) and solving for t_a

$$t_a < \left(\frac{NCV_2}{2K}\right)^2 = t_{a\,(\max)} . \tag{16}$$

Equation (16) is our first monitoring inequality and it is plotted in Fig. 4 for different RC products, and for the two extreme damping conditions, versus capacitance.

This formulation of $t_{a(\max)}$ includes an inherent safety margin with regard to monitoring the process since the time to accomplish solidification is not taken into account.

2.4 *Minimum Limits on Arc Duration*

Burnback (b) is the length of wire melted back during arcing. With negligible error, it can be assumed that the electrodes are touching at arc initiation. (A potential of 50 volts will not normally initiate an arc across the air gap until it has closed to approximately 0.00005 inch.)[4] Consequently, the distance advanced by the wire during arcing must be equal to the average wire velocity, U, multiplied by the arc duration. This product will be very nearly equal to the total melted wire length, differing only by the thin layer of molten copper on the wire and by the crater depression in the terminal. These are both relatively small and of opposite sign. Therefore,

$$b = Ut_a . \tag{17}$$

In order to melt the entire wire tip length, l,

$$b > l + \text{safety margin}. \tag{18}$$

If the wire velocity is measured by the time, t_v, for the wire to traverse contacts separated by l, then (18) reduces to the monitoring inequality:

$$t_a > t_v . \tag{19}$$

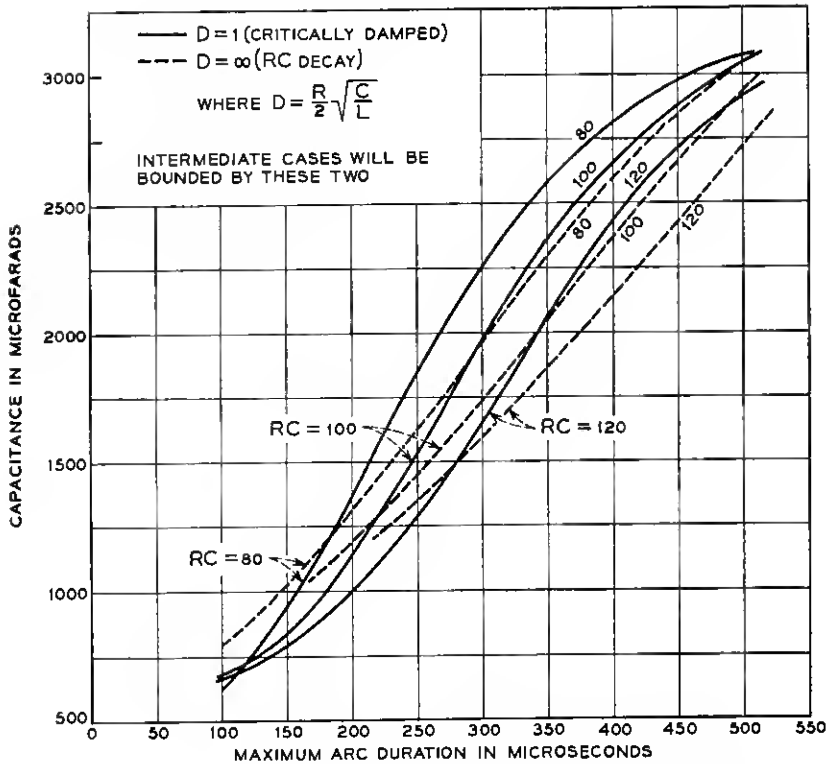

Fig. 4 — Computed curves for $t_{a(\max)}$: 24-gauge copper wire, nickel-silver terminal, welding voltage 50v, $V_1 = 20$v, $V_2 = 10$v, $K = 7$ watt(sec.)$^{\frac{1}{2}}$.

Preliminary tests indicated the need for another minimum limit on arc duration, $t_{a(\min)}$, independent of t_v, since a scattering of weak welds sometimes occurred at slightly longer arc durations than predicted by (18). In general, $t_{a(\min)}$ must be at least long enough to provide for sufficient melting energy; however, other reasons may make a longer time necessary. This is discussed further in Section V. On this basis,

$$t_a > t_{a(\min)} \tag{20}$$

where $t_{a(\min)}$ is determined empirically. For the tests reported in Section IV, $t_{a(\min)}$ was found to be 200 microseconds.

2.5 *Necessary Power Supply Capacitance*

The melting energy (E_M) necessary to remove the entire wire tip, assuming the molten metal is at its melting temperature, is

$$E_M = (T_M c + \lambda)\rho v. \tag{21}$$

where T_m is the metal melting temperature, c is the specific heat, λ is the latent heat of fusion, ρ is the metal density and v is the wire tip volume.

The necessary power supply capacitance, C, can be calculated from an energy balance

$$\tfrac{1}{2} E_H - Q = E_M . \tag{22}$$

Substituting in (12), (14), and (21) and evaluating for average damping conditions, for copper wire and for $t_a = t_{a(\max)} = 3RC$,

$$C \cong 600\alpha v \tag{23}$$

where α is a safety factor at $t_{a(\max)}$. In general, α must include allowances for the reduction in input energy resulting from shorter arcing times as well as the greater demand for energy resulting from the variational increases in tip volume. The safety factor at $t_{a(\min)}$, (β), will be, of course, smaller than α and may be evaluated from the following approximate relationship

$$\beta \cong \frac{1 - \exp\left(-t_{a\,(\min)}/RC\right)}{1 - \exp\left(-t_{a\,(\max)}/RC\right)}\,\alpha. \tag{24}$$

An independent measurement of the melted wire volume versus capacitance agreed closely with the volume predicted by (23).

2.6 *Monitoring Inequalities*

To recapitulate, the inequalities in (16), (19), and (20) restrict the allowable range of arc durations for percussive welding

$$\left\{ \begin{matrix} t_v \\ t_{a(\min)} \end{matrix} \right\} < t_a < t_{a(\max)} \tag{25}$$

where $t_{a(\min)}$ and $t_{a(\max)}$ are fixed limits evaluated either from the constants of the process or by empirical methods, and t_a and t_v are measurements made for each weld. The measurements of t_a and t_v can be made in a number of ways. Fig. 5 shows one method, in which contacts separated by the minimum burnback distance provide step voltages which are indicative of t_v, and a coil around one welding lead provides induced voltages at the beginning and the end of the arc which are indicative of t_a. These voltage indications are fed to a timer and alarm — any suitable apparatus capable of determining whether the monitoring inequalities in (25) are satisfied. Various other measurement methods might be em-

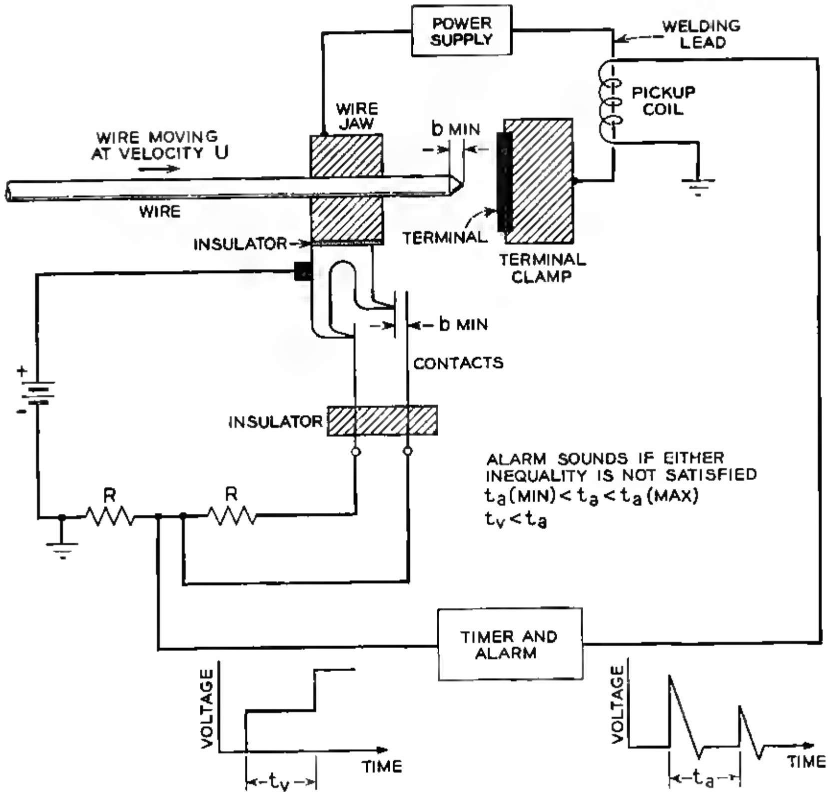

Fig. 5 — Wiring schematic of monitoring circuit.

ployed, such as a light beam and photocells in the case of t_v and the arc voltage change in the case of t_a .

III. OTHER CONSIDERATIONS

The described monitoring method naturally does not preclude the possibility of a defective weld. Other causes still exist.

3.1 *Bad Wire Tip*

Inconsistently or improperly formed tips are a potential hazard. Usually, monitoring will detect this condition since arc duration is sensitive to variations in either tip length or volume. Nevertheless, certain tip variations — for instance, variations in symmetry — are undetected by the measurement of arc duration.

3.2 *Arc Dispersion*

The wire as it approaches the terminal must "see" the terminal to the exclusion of any other metal at terminal potential. Otherwise the arc will spread and be weakened, resulting in poor welds despite monitoring.

3.3 *Mechanical Effects at Closure*

The most critical time in the weld process is, of course, when the two weld metals come together and fuse. The possible influences on weld strength at this time are manifold; the following are representative. At closure, the arcing surfaces should match reasonably well in order to achieve a uniform fusion zone. Also, any large disparity in contour will cause a time lag between initial electrode contact (arc extinguishes) and final full-area contact. The time lag is increased if the wire is appreciably decelerated. During such a time lag, premature solidification might be a problem in those areas that mate last. The shape of the original wire tip, especially its symmetry, plays an important role in determining how well the electrode surfaces will mate, since arcing generally is concentrated between the nearest points on the two electrodes.

With regard to impact forces at the weld interface, it has been found that up to a point these forces improve both connection strength and fatigue life. This might be attributed to various effects, some of which could be, (*i*) overcoming small contour differences on the arcing surfaces, (*ii*) heading, or increasing the area near the weld zone, (*iii*) strain hardening the copper above the weld, (*iv*) promoting better mixture in the fusion zone.

IV. DESCRIPTION OF TESTS

4.1 *General*

Welds were made for test under controlled laboratory conditions and monitored in accordance with the analysis. In order to test only the effects of the parameters in the monitoring inequalities, all other welding conditions were optimized to the best of our knowledge.

Wire tips were cut with a hand-held pair of diagonal wire cutters. Despite its seeming crudeness, this tip has been found to be sufficiently reproducible and has given good results in the past. The tip length on the wire averaged 0.019 inch with approximately half the volume of an equal length of wire. The wire was 24-gauge tinned copper.

The terminal was held flush with or slightly projecting from the ter-

miual clamp in order to minimize arc dispersion. The terminal was 0.025 inch x 0.062 inch nickel-silver.

The welding power supply contained 2300 microfarads capacitance. This value produces an adequate energy margin. No delay line or other type of network was used to supplement the capacitor bank.

The wire was accelerated with an adjustable tension spring and was permitted to fully impact into the terminal so that the weld interface experienced the complete impact forces. Weld strengths were measured by the "combined test" whereby the wire is bent over parallel to the terminal and pulled until either the wire or the weld fails. This test has proven to be more sensitive and more severe than a straight tension test. The break was classified as a "wire break" if the failure occurred in a portion of the wire completely above the terminal surface. Actually, these "wire breaks" occurred randomly along a span of wire of about three inches, so that usually there was very little difficulty in distinguishing a "wire break" from a "weld break." Furthermore, if a break occurred close to the weld-affected zone, and its classification was doubtful, it was usually taken to be a "weld break" since the probability is small that a "wire break" would occur randomly this close to the weld.

4.2 *Phase I*

The testing was divided into two phases. In Phase I, the burnback inequality at all times was satisfied, whereas the arc duration was varied in order to demonstrate that (16) and (20) are necessary conditions for optimizing the welding process. The arc duration was varied by means of changing the wire velocity. At least 600 welds were made and tested within each 50-microsecond interval between 150 and 500 microseconds, making a total of 4730 welds. The testing was not extended below 150 microseconds because of practical limitations of high wire velocity.

The following steps, based on the analysis, show the calculations made to determine the monitoring limits applicable to this first phase of testing.

(a) The welding circuit constants were determined by substituting measurements from an oscilloscope current trace into the theoretical current expression. Accordingly, the effective total series circuit resistance was calculated to be 0.040 ohm, the inductance 0.75 microhenry and the power supply capacitance 2300 microfarads. The capacitance figure agrees closely with an independent measured value. From (3) the damping ratio, D, becomes 1.1. The RC product becomes 92 microseconds.

(b) From Fig. 4, using the critical damping curves, $t_{a(\max)}$ is 320 microseconds.

(c) In accordance with previous tests at the same welding conditions, $t_{a(\min)}$ was taken at 200 microseconds.

(d) The average wire tip volume was measured to be approximately 3×10^{-6} cubic inches. Using (23), the safety factor (α) at 320 microseconds is calculated to be 1.25 for a capacitance of 2300 microfarads. The safety factor is reduced to about 1.15 at 200 microseconds using (24).

4.3 *Phase II*

In Phase II, the burnback was varied in order to demonstrate the necessity of adequate burnback (18). The burnback was varied from 0.012 to 0.022 inch to span the average tip length of 0.019 inch. At least 200 welds were made and tested within each 0.002-inch increment, making a total of 1126 welds. The test was planned to be within the 200 to 350-microsecond interval of arc duration at a constant wire velocity of 63 inches per second. The only welding parameter independently varied was circuit resistance. This method was chosen not only to facilitate a sensitive control of burnback but also to avoid the possibility of exceeding $t_{a(\max)}$, since it was desired in this phase to test only the effect of reducing burnback.

The computations of monitoring limits for Phase II follow. Since resistance was varied in this test, no one value of $t_{a(\max)}$ applies throughout. But to indicate a typical case, at the longest range of arc durations in this test (320–350 microseconds), the incremental resistance was approximately 0.060 ohm, making the total resistance 0.1 ohm. The RC product then is 230 microseconds and $t_{a(\max)}$ is calculated from (16) and Table I to be approximately 600 microseconds ($N = 15$; $\tau_a = 2.5$).

From (24), the safety factor for energy at 320 microseconds is approximately 1.0, which means that this is the minimum allowable arc duration on a "sufficient energy basis." The burnback at 320 microseconds and 63 inches per second is 0.020 inch, in good agreement with the average tip length (0.019 inch) and giving us a check on the calculations. Consequently, in this test we can expect weld quality to degrade for arc durations less than 320 microseconds.

V. DISCUSSION OF TEST RESULTS

5.1 *General*

The test results of Phase I, shown in Fig. 6, clearly demonstrate that, for the conditions of this test, the welding process is optimized when the arc duration is between 200 and 300 microseconds. Within this range, 99.2 per cent of the samples failed in the wire and 99.85 per cent of the samples exceeded 90 per cent of the wire strength.

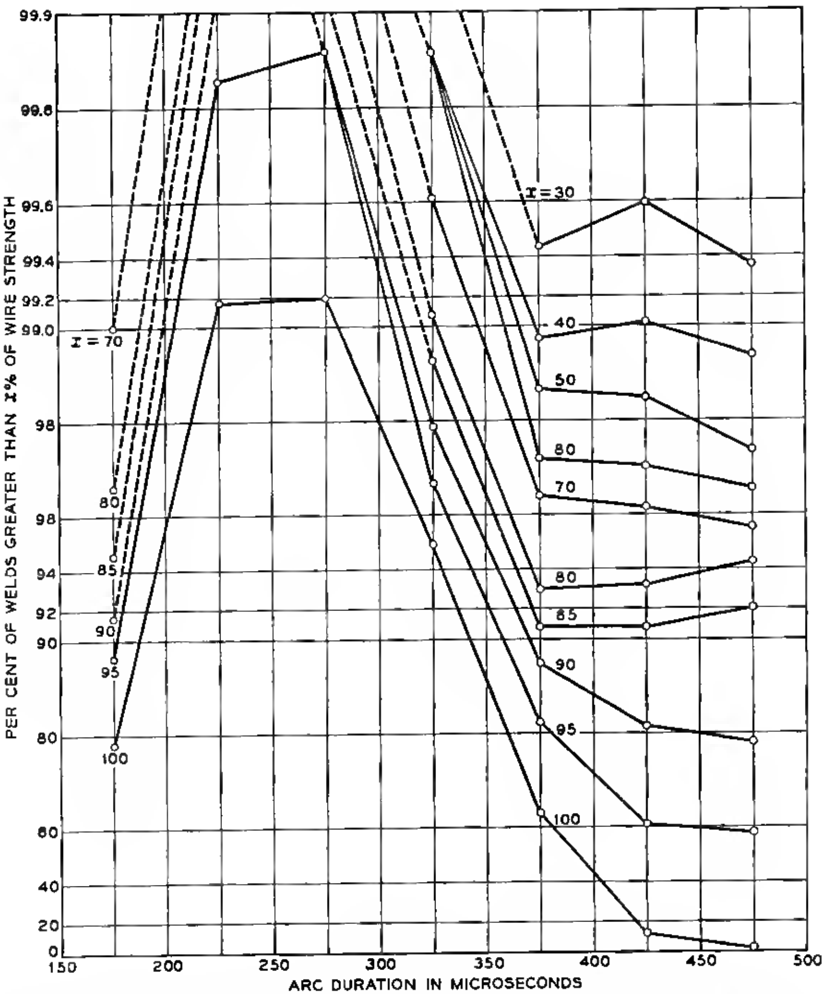

Fig. 6 — Results of test No. 1, weld strength vs arc duration: 24-gauge copper wire, nickel-silver terminal, capacitance 2300 μf, resistance 0.04 ohm, diagonal-cut wire tip, variable wire velocity.

The estimated limits of the optimum range, 300 and 200 microseconds, agree closely with both the results of previous tests and the analysis. At arc durations less than 200 microseconds there is a relatively fast dropoff in weld quality. At arc durations longer than 300 microseconds there is also a dropoff in quality, although not as rapid as in the first case. As the arc duration deviates further from optimum toward longer times, the

percentage of weaker welds begins to level off. Although this was unexpected, it may be explained plausibly on the basis of varying solidification time.

The time interval that can safely elapse after $t_{a(\max)}$ depends, of course, on the heat contained in an unknown thickness of molten film over the electrodes. This thickness is probably quite variable. At normal welding velocities, it is quite thin; however, there is evidence that it generally increases on the wire for longer arc durations (slower wire speed).[5] Therefore, the time to solidify the molten film will also be variable and will, in general, become longer at longer arc durations.

The results of the second phase of testing, shown in Fig. 7, indicate a rapid loss of weld quality as the burnback is decreased. In agreement with the preliminary calculations, the weld quality was relatively good for arc durations greater than 320 microseconds or burnback in excess of 0.020 inch.

5.2 *Mapping Over-all Test on Burnback vs Arc Duration Axes*

The results of the over-all test program can best be discussed with the aid of Fig. 8. On this figure, the over-all test range is mapped into five regions and the monitoring limits visually displayed with respect to these regions on a burnback versus arc duration axis. Some further explanation will be helpful in interpreting this figure.

For any weld, the average wire velocity during arcing and the duration of the arc may be measured. These measurements determine a point on Fig. 8, where the product of the measurements (burnback) is the ordinate and arc duration is the abscissa. As wire velocity is varied and a number of points are plotted, a curve takes shape. This curve relates the melted wire distance to the time after arc initiation for a particular set of circuit conditions and wire tip. Accordingly, the upper curve of Fig. 8 is the sketched-in melting curve for the welding conditions in the first phase of the test program. The lower set of curves is for Phase II, where each curve in the set would be determined by a corresponding value of circuit resistance. The intersection of a particular melting curve with a line of constant velocity locates the arc duration and burnback of a weld for the welding conditions corresponding to that melting curve. This point will be referred to as an "operating point" of the welding process. Naturally, there will be a statistical scattering of the data about the operating point due to normal test variations.

The first test phase extends over regions A, B, and C while the second test extends over regions D and E. Note that in Phase I the operating points coincide with a melting curve, while in Phase II the operating

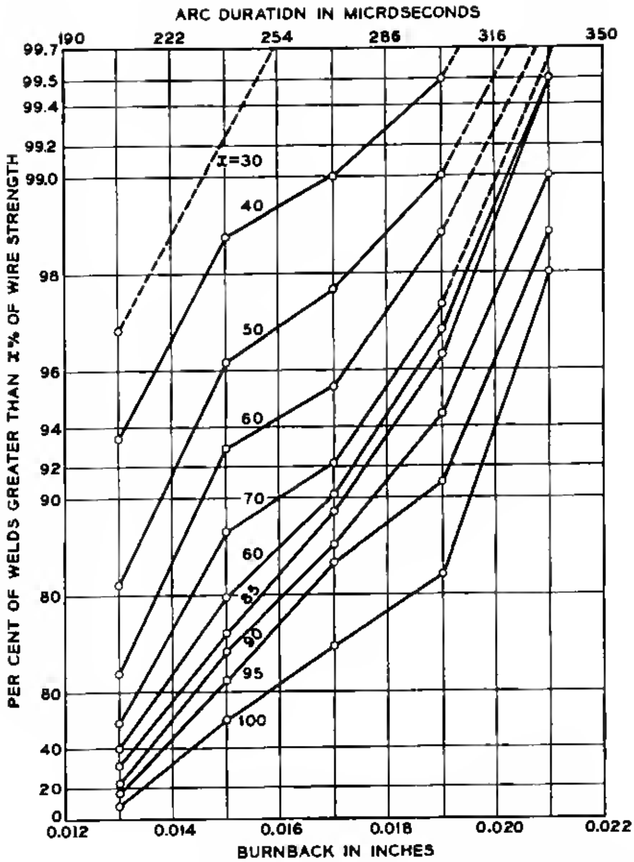

Fig. 7 — Results of test No. 2, weld strength vs burnback. Conditions same as test No. 1, except that wire velocity is constant 63 in/sec and resistance is varied.

points lie along the 63 inches per second velocity line. Table III summarizes the test results for the regions of Fig. 8 and indicates the monitoring inequalities which were violated in each case. The "order of merit" of weld quality is based on the test results in Figs. 6 and 7. Table III, in conjunction with Fig. 8, demonstrates the necessity of each of the monitoring inequalities.

In Fig. 8 it is seen that the constant burnback line of 0.020 inch forms the boundary between regions D and E. The fact that this boundary, only 0.001 inch more than the average tip length, effectively separates the good from the poor welds implies that burnback is the controlling factor in weld quality in Test Phase II. An independent

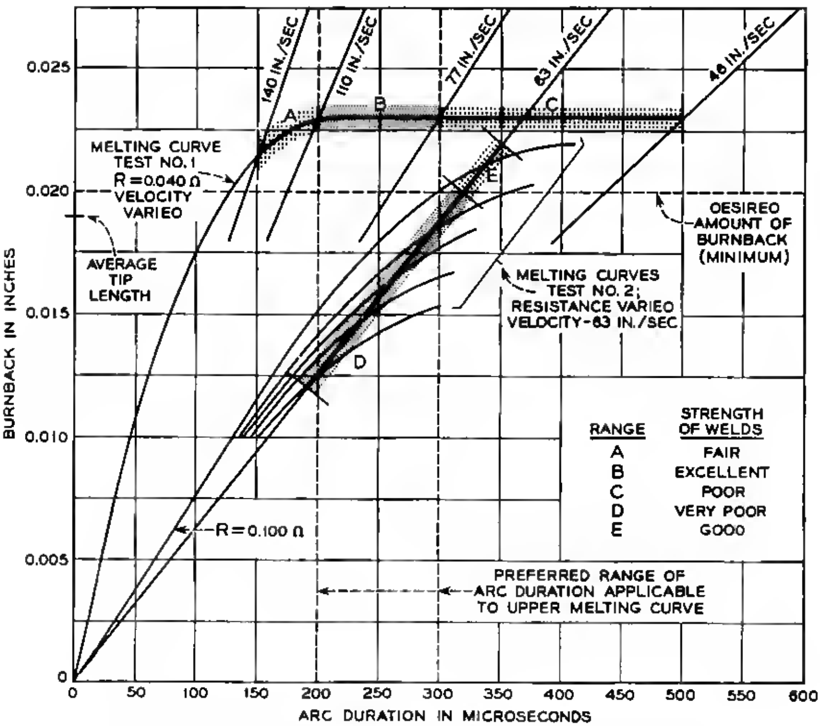

Fig. 8 — Graphical representation of over-all test program.

$t_{a(\min)}$ limit therefore is obviated in this case and the entries in the table agree with the burnback column. On the other hand, in region A, weld quality is poorer, despite an average burnback of 0.022 inch. Here $t_{a(\min)}$ is the controlling limit.

It is significant that there is this distinction in the controlling lower limit of arc duration, and the question is asked, Why does weld quality

TABLE III

Test Phase	Region	Weld Quality Order of Merit	$t_a < t_{a(\max)}$	$t_a > t_{a(\min)}$	$b > 0.020$, or $t_a > t_v$
I	A	3	Satisfied	Violated	Satisfied
I	B	1	Satisfied	Satisfied	Satisfied
I	C	4	Violated	Satisfied	Satisfied
II	D	5	Satisfied	Violated*	Violated
II	E	2	Satisfied	Satisfied*	Satisfied

* See Section 5.2.

drop off in region A? A comparison of welding conditions leads to some speculations as to the reasons. In region A, the electrodes close at the highest current density and with the fastest wire speed. It is reasonable that extremes in these variables could be undesirable. For instance, during the high current portion of the arcing period, the melting process and temperatures are undergoing rapid transitions. Probably some vaporization is taking place. If the wire speed is fast, closure occurs during this high current portion of the arcing period. Under such volatile conditions, the weld process is apt to be erratic. A relatively slower speed would lengthen the arc duration and allow conditions to become more stable.

In general, poor weld quality will result if the wire speed is allowed to become too slow. This is seen clearly in Fig. 8 by letting the operating point move to the right along the upper melting curve. By the time the wire speed has decreased to 63 inches per second, the "operating point" is well into the poor area in region C. However, if we now hold the wire speed constant and add 0.060 ohm to the welding circuit, the operating point shifts into region E, and to a different melting curve, resulting in an improvement in weld quality. Hence, a change of circuit resistance in this case will restore the good weld quality which had been lost by slowing the wire speed. This suggests that the slow wire speed is responsible for the poor weld quality, not through any mechanical effects, but rather by lengthening the duration of the arc past a maximum safe limit for a particular melting curve.

5.3 *Statistical Interpretation of Data*

The data of Fig. 6 are replotted in Fig. 9. There are seven distributions shown, one for each 50-microsecond increment of arc duration. In general, all the distributions consist of two portions. The first portion is the distribution of welds which failed near the weld at less than wire strength, while the other is the distribution of welds which failed in the wire. In each case the portions representing weld failures are fairly linear, with a steep slope; however, in some cases the lines curve as they join the wire break portions. Because of the choice of ordinate, the portions representing wire failures are horizontal straight lines at 100 per cent of wire strength.

To aid in interpreting these curves, the wire strength is thought of as an upper cutoff boundary on the weld strength. The following example is an analogous situation: suppose pennies were being pitched to a line. The density of pennies would be normally distributed on either side of the line. Now suppose that an adhesive-coated wall were placed at the line, all other things remaining the same. All the pennies which would

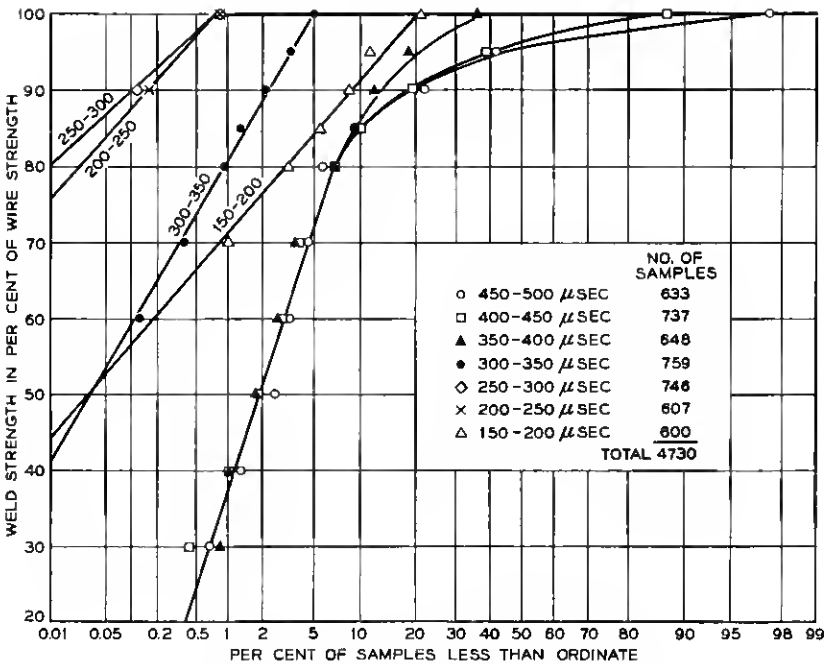

Fig. 9 — Cumulative distribution of data from test No. 1.

ordinarily pass over the line now hit the wall and stick to it. A portion of a normal distribution is left to one side of the wall and all the remaining pennies stuck to the wall. Plotting the distribution of pennies around the wall would result in a distribution similar to that found in the case of percussive-welded connections. The pennies which stick to the wall represent wire breaks, and the truncated normal distribution of pennies to one side of the wall represents weld breaks.

It appears, therefore, that the distributions of weld strengths in Fig. 9 are normal below some value of weld strength since the lower strength portions of all the curves are essentially straight lines. Therefore, the probabilities associated with the lower tails of the distribution can be read directly. The two curves which represent the welds satisfying the monitoring inequalities approach the 0.01 percentage point of the distribution at approximately 76 per cent and 80 per cent of wire strength. All the other curves are 45 per cent of wire strength or less at this equivalent point on the distributions. Thus these data indicate that, with monitoring, there is a much smaller probability of finding weak welds than in an equivalent size sample of unmonitored welds.

Based on these data, it appears that percussive welding is capable of meeting present quality objectives of a maximum defect rate of one in ten thousand, a defect being defined as a connection which is weaker than 60 per cent of wire strength.

5.4 *Generalizations Regarding Weld Strength Data*

The following are some typical characteristics of the strength distribution of low-voltage percussive welds. These generalizations are not drawn solely from the present data, but have been observed repeatedly in various sets of data.

(a) When the process is optimized, the distribution of weld strength is bunched tightly around the wire strength.

(b) When the process is off optimum, a long tail develops in the distribution of weld strength. This tail is made up of relatively weak welds which usually comprise a small percentage of the total number of welds in the distribution. The tail is an incomplete normal distribution, bounded on the upper side by the wire strength.

(c) The over-all quality of a population of percussive welds is defined completely in terms of the tail of the distribution.

The following factors all tend to limit an effective assurance of quality based on small sample size destructive testing:

(a) Only a very small percentage of the data yields useful information regarding the tail of the distribution.

(b) The large standard deviation of the tail makes large sample sizes necessary if confidence in the sampling is not to be sacrificed.

(c) The allowable percentage of defects is small (one in ten thousand). Therefore, large sample sizes are required in order to gain a reasonable degree of confidence in the sampling.

The conclusion, based on these factors, is that small sample size destructive testing alone cannot assure quality levels of less than one defect in ten thousand. The sample size required to assure this degree of connection reliability, with a reasonable degree of confidence, would be prohibitive from a cost standpoint.

VI. SUMMARY AND CONCLUSIONS

1. It is characteristic of the low-voltage percussive welding process that the relatively weak welds in a population will be contained in a long tail of the distribution. The welds in this tail are distributed normally, with large variance, and are bounded on the high side by the wire strength. The vast majority of welds are not contained in the tail and have essentially the distribution of the wire strength. This double

nature of the over-all distribution, unfortunately, severely limits the effectiveness of small sample size destructive testing.

2. In view of the difficulties encountered in statistical sampling by destructive testing and because of the lack of any effective and practical method of testing nondestructively, it was sought to attain consistently reliable percussive welds by continuous control of the process, i.e., by monitoring certain important welding parameters as each weld is made.

3. Preliminary tests indicated that the time duration of the arc was the most sensitive over-all indicator of variations in the process. The effectiveness of arc duration is further increased if the measurement is related to the approach velocity of the wire. Since both these parameters are relatively easy to measure, arc duration and wire velocity were chosen as the most effective and practical measurements for purposes of monitoring.

4. It was found that there is a range of arc duration for which the process is optimized. Weak welds which occur at longer arc durations are attributed to excessive heat conduction losses which result in premature solidification of the molten metal film over the arcing electrodes. An analytical derivation is made for a maximum allowable arc duration, which is defined as that time when heat conduction losses begin to exceed power input to the weld.

5. At excessively short arc durations, weak welds can be attributed to insufficient arc energy, which results in insufficient burnback on the wire to produce a full-area weld. Accordingly, the minimum allowable arc duration is shown to be the time required for the moving wire to travel a distance equal to its tip length.

6. In addition to satisfying the proper limits of arc duration, other conditions should be satisfied in order to attain good welding results. These include a properly and consistently made wire tip, no excessive spreading of the arc, and sufficient force between electrodes at contact to affect good mating and fusion.

7. A test program of nearly 6000 welds confirmed that the low-voltage percussive welding process is optimized when the arc duration is between an upper and a lower value. Furthermore, these limits, as indicated by the data, agree with the predicted values from the analysis and earlier testing.

8. Based on the data of weld strength for welds satisfying the monitoring inequalities, the low-voltage percussive welding process is capable of meeting present quality assurance objectives of less than one defective connection in ten thousand, where a defective connection is defined as one weaker than 60 per cent of the wire strength.

VII. ACKNOWLEDGMENTS

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